SM single-top production at hadron colliders

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Abstract. We give an overview of the status of theoretical predictions for single-top production in the Standard Model. We focus in particular on recent developments, including calculations of off-shell effects at next-to-leading order beyond the narrow-width approximation, all-order resummation of soft corrections and matching of next-to-leading order parton-level results to Monte Carlo parton showers.

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1. Introduction

The hadroproduction of a single top quark, first observed at the Tevatron [1, 2], is a process of significant phenomenological relevance, providing informations complementary to those that can be obtained from top-quark pair production. Being mediated by electroweak-boson exchange, single-top production represents an unique window into the charged-current interactions of the top quark, enabling tests of the $V-A$ structure of the Wtb vertex and a direct extraction of the CKM matrix element V_{tb}, which is at the moment only indirectly constrained. Single-top production is also very sensitive to new-physics effects and anomalous couplings, whose strength can be assessed by a precise measurement of the production cross sections. Furthermore, single-top production probes the bottom-quark parton distribution inside the proton, which at present is weakly constrained by other experimental data. For these reasons, the study of the production of a single top quark will be an important part of the physics programme of the Large Hadron Collider (LHC) at Cern, where several results are already available [3, 4, 5, 6].

In the Standard Model (SM) single-top production is customary divided into three production channels: t-channel production, which involves the exchange of a space-like W boson, s-channel production, where the intermediate W boson is time-like, and associated production of a top quark and a real W boson. The tree-level Feynman diagrams contributing to the three different channels are shown in Figure 1. Both at Tevatron and the LHC the t-channel process is the dominant one, accounting for about 63% and 71% of the cross section, respectively [7] [1]. At the Tevatron s-channel production is the second most important channel ($\sim 30\%$) but it is negligible at the LHC, where Wt production has the second largest cross section (about 25%). It has to be mentioned that the classification into three separate channels is delicate and somewhat artificial, since, starting at next-to-leading order (NLO) in α_s t-channel and s-channel production mix with each other. Furthermore, at NLO Wt production interferes with $t\bar{t}$ production, which makes

[1] The relative size of the three channels changes slightly depending on the theoretical prediction used.

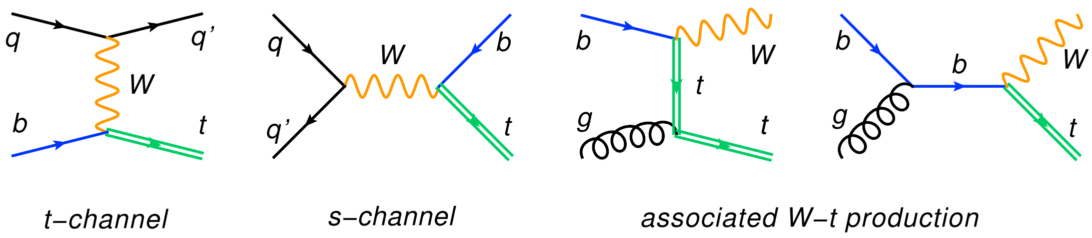

Figure 1. Tree-level single-top production in the Standard Model.

the theoretical definition of two separate processes difficult and the extraction of the Wt signal from the much larger $t\bar{t}$ background experimentally challenging. The prospects of a meaningful theoretical and experimental definition of the Wt process were thoroughly investigated in [8, 9].

NLO QCD predictions for single-top production in the approximation of a stable top have been available for more than ten years, both at the inclusive [10, 11, 12, 13, 14] and differential level [15, 16]. Electroweak and SUSY-QCD corrections have been also computed and found to be small, typically below 5% of the tree-level result [17, 18]. More recently the relation between the five-flavour (5F) and four-flavour (4F) scheme at NLO has been investigated [19, 20]. The two approaches differ in the treatment of the initial bottom quark in t-channel single-top production, which originates from a non-vanishing bottom PDF in the 5F scheme, and is generated by splitting of an initial gluon in the 4F scheme. In [19, 20] the two schemes were found to be in good agreement at NLO, except for distributions related to the spectator b-jet, which in the 5F scheme are effectively LO observables. Beyond the stable-top approximation, NLO predictions for single-top production and decay have been computed in the Narrow Width Approximation (NWA) [21, 22, 23, 24, 25, 26], and were implemented in the numerical code MCFM [27]. In this approach the top quark is produced on shell and let decay, with full spin correlations, to its final products.

Recent developments beyond a fixed-level NLO calculation for production and decay of an on-shell top include the calculation of off-shell and non-factorizable corrections to t-channel and s-channel single top production, soft-logarithm resummation of the partonic cross sections and the matching of NLO parton-level calculations to Monte Carlo parton showers. We will cover these topics in the following sections. New-physics effects in single-top production in extensions of the SM have also been widely investigated, but they are beyond the scope of this review.

2. Off-shell and non-factorizable corrections to single-to production

In the framework of the NWA NLO contributions are given by factorizable corrections to the on-shell production and decay of the top quark, while non-factorizable contributions connecting initial- and final-state light partons, as well as off-shell and finite-width effects, are neglected. These terms are small for the total cross section, of order of the top width-to-mass ratio $\Gamma_t/m_t \sim 1\%$, due to large cancellations between virtual and real corrections. However non-factorizable corrections could be a priori large for exclusive observables, like arbitrary kinematical distributions. This was investigated in [28, 29], where off-shell and non-factorizable corrections to t-channel and s-channel production were computed.

The calculation of [28, 29] is based on an effective-field theory (EFT) description of the single-top production process [30], built upon the hierarchy $\Gamma_t \ll m_t$. In this approach contributions to the amplitude are divided into hard corrections, encoding physics at the large momentum scale $q \sim m_t$, and soft contributions, describing the long-distance physics associated with the low scale $q \sim \Gamma_t$. In the effective theory only soft modes are described by dynamical fields, while hard contributions are encoded into the effective couplings (matching coefficients) of the

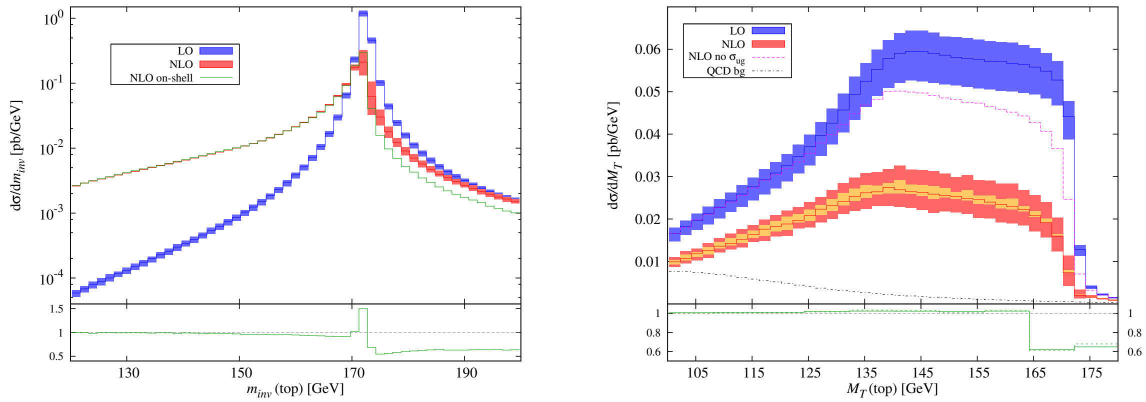

Figure 2. Top-quark invariant-mass (left) and transverse-mass (right) distributions for t-channel single top production at the LHC with $\sqrt{s} = 7\,\text{TeV}$ [29]. See the text for explanation.

EFT Lagrangian. In this framework an NLO calculation requires $\mathcal{O}(\alpha_s)$ corrections to the hard matching coefficients and one-loop soft contributions to the EFT matrix elements. These can be defined in terms of an expansion of full QCD diagrams in hard and soft momenta using the method of regions [31].

Two examples of the effect of off-shell and non-factorizable corrections are shown in Figure 2, where the top invariant-mass and transverse-mass distributions for t-channel single-top production at a 7 TeV LHC are given for $m_t = 172\,\text{GeV}$ [29]. The blue and red curves represent the LO and NLO off-shell result, respectively, the bands the corresponding uncertainty obtained from scale variation. The green curve in the lower inset is the ratio of the NLO on-shell prediction in the NWA to the off-shell result. One can seen that off-shell and non-factorizable effects are large around the peak of the invariant-mass distribution, with deviation of up to 50% from the on-shell result. However these effects change sign around the peak, which explains the small corrections in the transverse-mass distribution for $M_T < m_t$, where large cancellations occur due to averaging over different values of the invariant mass for a fixed M_T. These cancellations are less effective close the the distribution edge $M_T \sim m_t$, due to phase-space restrictions. In this region off-shell effects are large, about 40% of the NLO on-shell result, and are necessary for a reliable theoretical prediction of the distribution.

3. Resummation of soft logarithms

Single-top production observables contain logarithmic contributions $\alpha_s^m[\ln^k s_4/s_4]_+$ (with $k = 0, ..., 2m-1$) related to suppression of soft-gluon emission near kinematical thresholds, with s_4 the (observable dependent) kinematical variable that vanishes at threshold. Such terms can give a sizeable contribution to the cross sections, and all-order resummation of these threshold terms can be used as a mean to improve fixed-order predictions. For single-top production, this has been studied separately by two different groups, using a formalism based on resummation in Mellin-moment space [32, 33] and a framework involving soft-collinear effective theory (SCET) and renormalization group evolution equations [34, 35].

Both methods are based on the factorization of the cross section at threshold into a hard function H describing the short-distance scattering process, a soft function S encoding soft radiation and additional terms accounting for collinear emission from initial- and final-state particles. The all-order resummation of soft contributions in S is controlled by matrix-valued soft anomalous dimensions Γ_s, which have been computed up to two loops [36, 37, 38, 39].

Explicit results for the NNLL resummation of the single-top production cross section are

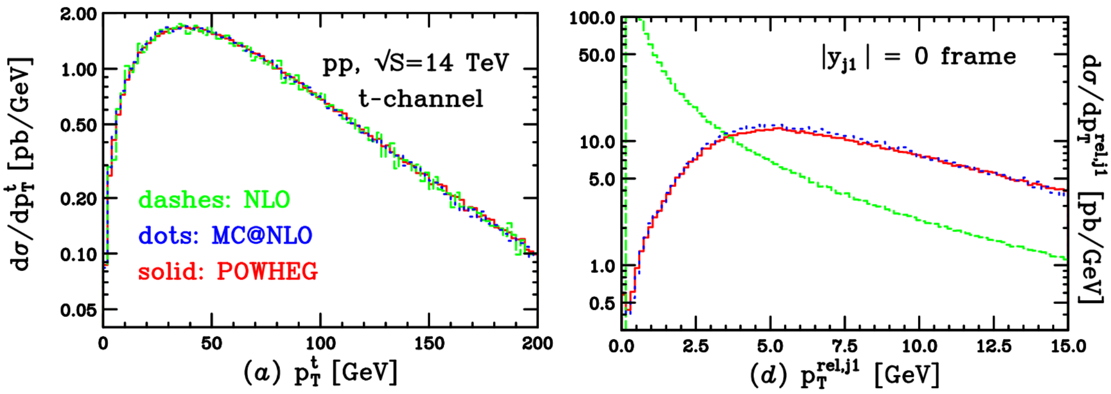

Figure 3. Comparison of fixed-order NLO results for t-channel single-top production at the LHC with MCPS results obtained with POWHEG and MC@NLO (plots taken from [44]). See the text for explanation.

available for the three separate channels in the Mellin formalism [40], and for t-channel [35] and s-channel production [34] in the SCET approach. Both formalisms find small resummation effects, of order of few percents, in t-channel single-top production. On the other hand, in s-channel production the results of the two groups show bigger discrepancies, with far larger soft effects (13%−15%) found in the Mellin approach [36]. This discrepancy has not been investigated yet. However it should be noted that in the two approaches different kinematical variables s_4 are chosen, so that sets of different logarithms are resummed. While the two calculations should give formally equivalent results at NNLL accuracy for the total cross section, power-suppressed contributions, which are not controlled by resummation, could be numerically important and be responsible for the observed differences.

4. Matching of NLO results to Monte Carlo parton showers

While a fixed-order NLO calculation gives an accurate description of wide-angle radiation, in the low p_T region multiple collinear emission becomes important and has to be taken into account. Furthermore, to realistically describe physical final states, a parton-level calculation has to be interfaced to some kind of hadronization model describing the evolution of energetic coloured partons into colour-singlet hadronic states. This can be done in the framework of Monte Carlo parton showers (MCPS), which gives a probabilistic description of multiple collinear splitting and can be easily interfaced to one's preferred hadronization model. Recently a lot of effort has been put into the matching of NLO fixed-order calculations to Monte Carlo parton showers, in an attempt to obtain a framework in which both large-angle radiation at NLO and all-order collinear emission are correctly described. This requires addressing double-counting issues in the collinear region, which has been consistently done in two different frameworks, MC@NLO [41] and POWHEG [42]. The production of a single top have been implemented in both approaches [43, 44, 45].

Figure 3 shows the comparison of the two NLO Monte Carlo showers with a fixed-order NLO result for the specific case of t-channel single-top production at the LHC with $\sqrt{s} = 14\,\mathrm{TeV}$. The two plots (taken from [44]) represent the top-quark transverse-momentum distribution (left) and the distribution of the relative momentum of all the partons clustered inside the hardest jet, p_T^{rel,j_1}, in the reference frame in which the rapidity of the jet is zero. In both cases the good agreement between the results of the two NLO parton showers is evident. For the top transverse-momentum distribution one can also note the good agreement between the fixed-

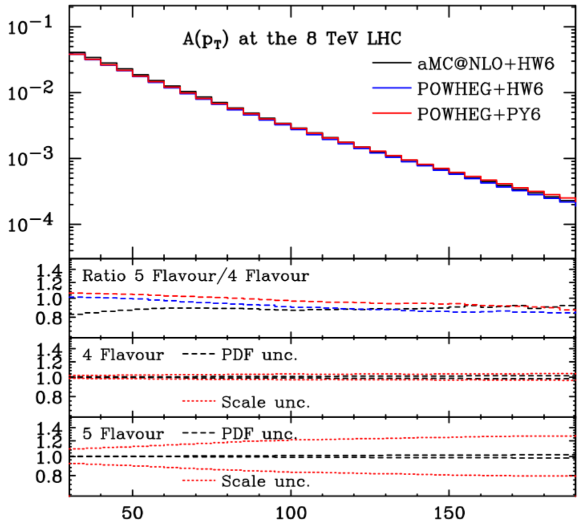

Figure 4. Acceptance as a function of the second-hardest b-jet at the 8 TeV LHC in the 4F scheme. Main plot: results for MC@NLO and POWHEG interfaced to Herwig and Pythia. Lower insets: ratio of the results in the 5F and 4F scheme and scale and PDF dependence of the 4F and 5F prediction computed with MC@NLO. See [46] for details.

order NLO prediction and the showered results. This is not the case for p_T^{rel,j_1}, where the parton-shower and fixed-order results show stark differences. This is expected, since the total relative momentum gives a measure of the spreading of the hardest jet, whose correct description requires the inclusion of multiple collinear emission when $p_T^{\mathrm{rel},j_1} \to 0$. Comparisons for the s-channel process and associated tW production [45] have shown a similar good agreement between MC@NLO and POWHEG, and confirm the importance of a NLO parton-shower treatment to correctly describe observables in both the small and large transverse-momentum regions.

Recently a comparison of the two NLO MCPS frameworks has also been performed in the four-flavour scheme [46]. Good agreement was again found between POWHEG and MC@NLO. As already observed for the fixed-order NLO cross section [19, 20], a comparison of results in the 4F and 5F schemes at the parton-shower level shows that the two descriptions are consistent at NLO, though the former gives more accurate predictions for observables which are related to the spectator b-jet. This can be seen for example in Figure 4, where the acceptance $A(p_T) = 1/\sigma \int_{p_T}^{\infty} dp_T^{(j_b,2)} \partial\sigma/\partial p_T^{(j_b,2)}$ is shown as a function of the transverse momentum of the second-hardest b-jet. From the insets is clear that the 4F scheme result has a much smaller theoretical uncertainty, though 4F and 5F predictions are consistent within their respective errors.

5. Conclusions

In view of its phenomenological relevance, in the last few years a lot of effort has been put into providing an accurate theoretical description of single-top production at hadron colliders. State-of-the-art results are represented by fixed-order NLO predictions matched to Monte Carlo parton showers, which provide an exact NLO description of the first emission and resum all-order radiation in the collinear region. In this framework the production and decay of the top quark is treated in the on-shell approximation. Studies of off-shell and non-factorizable effects have been performed for t-channel and s-channel production, and they have shown that these effects, though most of the time small, can be enhanced close to kinematical thresholds, and should be taken into account for a correct description of the shape of distributions close to kinematical edges. Resummation of Sudakov logarithms related to soft-gluon emission has also been studied by two different groups. In both cases, small resummation effects were found for t-channel production, but somewhat contrasting results were presented for s-channel production, which would motivate a further investigation of these effects.

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